# POSSIBILITIES OF INDUCTION HEATING INSTALLATIONS BASED ON THREE-PHASE LINEAR INDUCTORS

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***Abstract - The features of induction heating installations in a traveling magnetic field are considered. The expediency of using double-purpose linear induction machines and the prospects of using linear inductors creating opposite direction traveling magnetic fields are shown.***

***Keywords - induction heating, traveling magnetic field, combined heating, opposite direction traveling magnetic fields, research results.***

## I. Introduction

Induction heating installations are increasingly used in the metal processing industry, primarily in the heating of metal blanks or products for plastic deformation (pressing, stamping, rolling, etc.) and heat treatment (surface and bulk hardening, annealing, tempering, etc.). The main directions of improving technology and induction heating plants are mechanization and automation of processes, increasing the accuracy of maintaining the regime, increasing the economy of plants. In the aggregate, such tasks are solved in the creation of flexible automated technological complexes, including in their composition induction heating installations of continuous or periodic action. Automated induction heating lines are characterized by the modular formation of induction heaters, the translational or reciprocating movement of metal, the use of heating devices of different design and the principle of operation in one line [1-3]. In view of these requirements, it is sometimes expedient to use induction heating installations with running or rotating magnetic fields, in which both the thermal and mechanical effects of the magnetic field are useful.

Work on the use of traveling or rotating magnetic fields in induction heating installations was begun as far back as the 1980-1990s [4-11]. In particular, in the Urals State Technical University - UPI (now the Ural Federal University) in cooperation with the Ural Scientific Research Institute of Technology (UralNITI), the possibilities of creating a flexible automated line for low-temperature induction tempering of steel strips using three-phase linear inductors operating at an industrial frequency (50 Hz) [7, 9 ]. The works of that period made it possible to identify the main advantages of induction heating installations with a traveling magnetic field, consisting in the following:

1. The specific electromagnetic power transmitted from the inductor to the heated charge increases.
2. There is the possibility of purposeful use of electromagnetic forces to create production lines (heating and moving products in a traveling magnetic field, heating and tensioning of metal bands, etc.). On the contrary, the action of parasitic electromagnetic forces that occur in single-phase installations is eliminated.
3. Electromagnetic power in a heated metal in the case of a traveling magnetic field is distributed more evenly than in the case of a pulsed field, which causes the temperature to equalize.
4. There is an additional possibility of adjusting the heating parameters due to a change in the speed of movement of the heated articles.
5. When three-phase inductors are used, the operation of the power supply system is improved by balancing the phases and increasing the power factor of the units.
6. The level of acoustic noise and vibration is reduced.

At present, the development of induction heating installations in a traveling (rotating) magnetic field is facilitated by the appearance of powerful three-phase sources of increased frequency and the appearance of high-coercive permanent magnets, enabling the creation of energy-efficient induction heaters with a rotating magnetic field of adjustable frequency [12-13]. New possibilities arise when linear inductors with opposite direction traveling magnetic fields are used in induction heating lines, which, besides heating, can control the movement of the heated metal and it's positioning in the working zone [14]. All this makes actual the continuation and development of scientific research work in the direction of creating installations for induction heating in a traveling magnetic field.

## II. The Methodology and Results of Research

In the scientific laboratory of the Department of Electrical Engineering and Electrotechnological Systems of the Ural Federal University, studies of induction heating processes in traveling magnetic fields are carried out in [7, 9]. In particular, the processes under different schemes of winding of linear induction machines (LIM) are studied. One of the used variants of the LIM windings inclusion circuit, illustrating the control possibilities of the magnetic fields of the inductor, is shown in Fig. 1.

This circuit allows the use of the inductor power connection through LIM (L1C, 1C2, 1C3, 2C1, 2C2, 2C3) motor clamps or zero points of parallel winding sections (1N, 2N). At the same time, by changing the phase alternation in parallel sections, it is possible to form magnetic fields traveling in one direction, or opposite direction traveling magnetic fields, creates pulsating magnetic fields with different pole divisions, and superimposes traveling and pulsing magnetic fields.

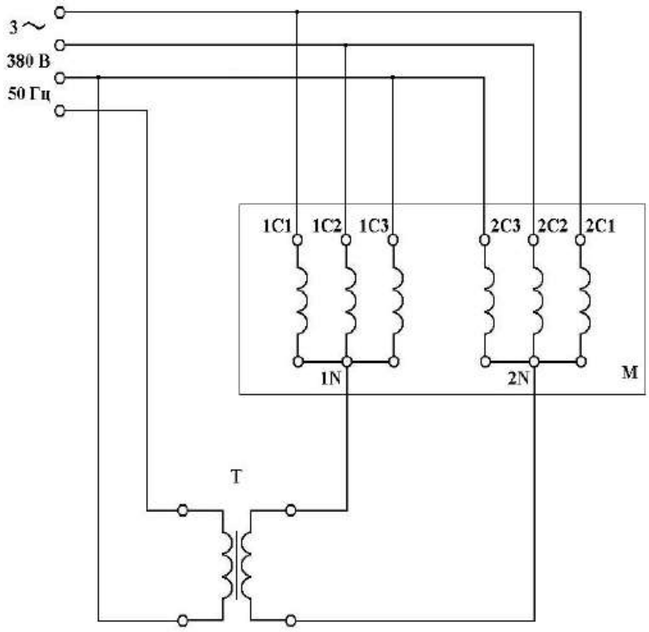


Fig. 1. Scheme of inclusion of windings of laboratory LIM used for induction heating

At the first stage, in the course of experimental studies of the described installation, the temperature distributions in the heated steel strip were evaluated upon exposure to it by various fields created by a single-sided linear inductor. For example, in Fig. 2 shows temperature distributions along the length of the steel strip along the inductor for cases of traveling (T) and transverse pulsating (P) magnetic fields with the same pole pitch ($\tau$ = 180 mm). Steel strip thickness of 15 mm and a width of 125 mm, equal to the width of the linear inductor, was located at a distance of 6 mm from the surface of a single-sided linear inductor. For the possibility of long-term measurements using an uncooled LIM, the linear current load of the linear inductor was only $A_1$ = 200 A/cm. Temperature measurements were made by the KSP-4 potentiometer using chromel-alumel thermocouples. The thermocouples were welded to the surface of the strip along its axis in increments of 36 mm.

The diagrams obtained with the help of the potentiometer recorder allow controlling the temperature variation of the steel strip in time at different points along its length. The temperature distributions shown in Fig. 2, were achieved 4 minutes after the inductor was turned on. At such a heating time, the influence of the heat transfer processes on the temperature distribution is still insignificant. Therefore the temperature distribution corresponds to the distribution of losses from eddy currents induced in the strip.

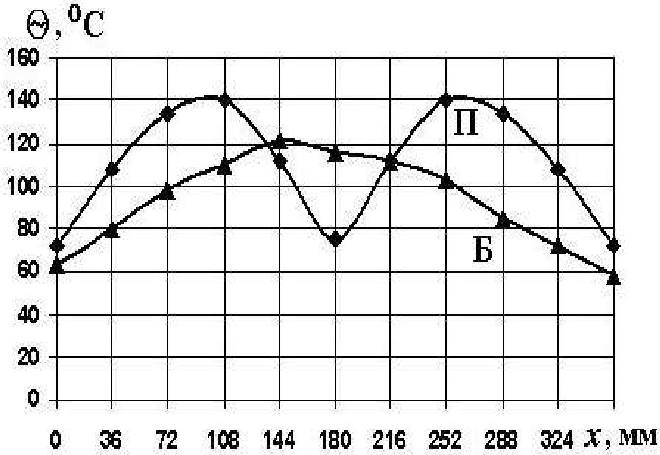


Fig. 2. Temperature distribution along the length of the steel strip heated in the transverse pulsating (P) and traveling (B) magnetic fields

First of all, a different character of the temperature distribution attracts attention (Fig. 2). When heated in a transverse pulsating field, the secondary eddy-currents are closed along the contour enclosing the magnetic flux. This leads to a significant uneven distribution of temperatures, and in particular to a temperature dip in the central part. When heated in a traveling magnetic field, the temperatures in the central part of the strip are equalized. The decrease in the heating of the strip at a distance from the center is due to the weakening of the magnetic field at the edges of the linear inductor. The influence of this factor decreases with increasing number of poles of the inductor. An additional advantage of induction heating devices in a traveling magnetic field is a significant increase in the power factor to a level of 0.55-0.60 as compared with the values of 0.35-0.38 in variants with a transverse pulsating field.

Experiments with an increase in the current load of a single-sided linear inductor to $A_1$ = 400-500 A/cm with a heating time of 5-7 minutes have shown that it is possible to reach the heating temperatures at 300-400 ° C necessary for low-temperature tempering of the steel strip. With such a current load cooling the linear inductor requires winding the windings using low power fans. When using two linear inductors located at the top and bottom of the steel strip (two-sided induction heating) the heating time is halved.

The advantage of the variant with a double-sided linear inductor is also the possibility of exciting a longitudinal (with respect to the strip) magnetic flux, at which temperature equalization over the width of the steel strip is achieved. This is illustrated in Fig. 3, where estimates of the non-uniformity of the induction heating of the strip in the transverse direction with variations in its width (Ln) are given. The relative superheat of the edge of the strip in comparison with its center is given for three methods of excitation of a traveling magnetic field: 1 - two-sided excitation with a longitudinal magnetic flow, 2 - two-sided excitation with a transverse flow, 3 - single-sided excitation. Estimates for all options are given based on the results of a two-minute heating. It is easy to see that in the case of a two-side induction heating with a longitudinal magnetic flux, a lesser uneven temperature of the strip is observed. For example, if the width of the strip varies within 90-160 mm, the underheating of the edge of the strip does not exceed 5%.

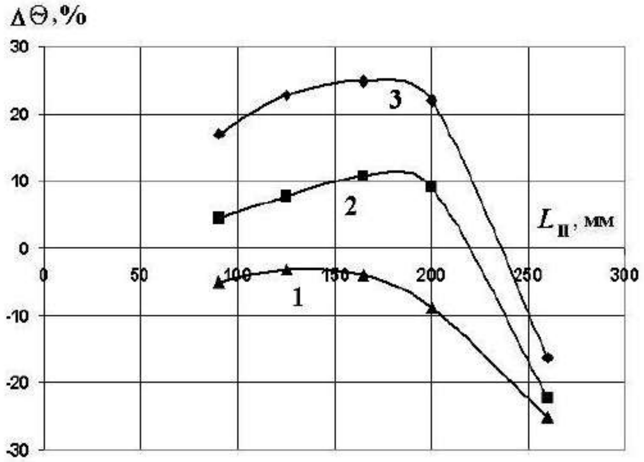


Fig. 3. Estimation of the non-uniformity of the temperature distribution over the width of the heated steel strip for different methods of excitation of the traveling magnetic field

An additional equalization of the temperature along the length of the steel strip can be achieved by superimposing traveling and pulsing magnetic fields with a two-current feed of a linear inductor. In confirmation of Fig. 4 shows the experimental characteristics of induction heating of steel strips obtained for such a case with single-sided excitation of traveling magnetic fields (single-sided linear inductor). At the same time, the traveling magnetic field was created by feeding the windings from the three-phase network through the motor clamps, and pulsating - by feeding the same windings from the single-phase network through the separation transformer and zero points, as shown in Fig. 1. In the described experiment, the zero points of neighboring inductors were used. For comparison, Fig. 4 shows the heating curve in a pulsed field. The current load of the inductor was chosen from the condition that the losses in the windings were equal in both cases. As in the case shown in Fig. 2, the temperature distributions reached after 4 minutes after the start of heating are shown. From Fig. 4, it can be seen that the distribution of temperature in the longitudinal direction is substantially equalized by the version of the two-current supply of the linear inductor. Single-phase LIM power through the zero points of the windings can be used to control the heating intensity. In this case, if necessary, it is possible to regulate not only the magnitude of the current, but also its frequency.

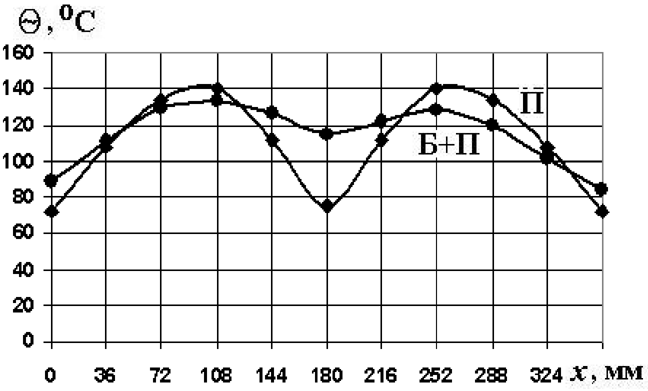


Fig. 4. Temperature distribution along the length of the steel strip when superimposed pulsating and traveling magnetic fields (T + P)

This technical solution with two-current LIM power requires two linear inductors having two zero points of the windings connected to a "star". This makes it possible to control the movement of the strip in the heating line due to electromagnetic forces acting on the metal strip. It is not difficult to provide such connection of inductors to a three-phase network, which will provide the opposite direction of electromagnetic forces of neighboring LIM. In this case, by regulating the currents in the inductors, you can achieve the movement of the band at a given speed, its reciprocating motion and positioning. Such devices, providing controlled movement and heating of metal, can be called double-purpose LIM.

Even wider possibilities arise when using induction heating devices in a traveling magnetic field linear inductors having parallel sections of windings and creating opposite direction traveling magnetic fields. The scheme of such a double-purpose LIM is shown in Fig. 1. As noted earlier in [14], when implementing an LMM with opposite direction traveling magnetic fields, different schemes for connecting windings can be used. In this case the LIM variants will differ by the distribution of magnetic fields, electromagnetic forces and losses in the secondary element, which creates new possibilities for realizing the modes of displacement and heating. The number of possible LIM variants in single- or two-sided execution, creating the opposite direction traveling fields, is dozens. This necessitates an additional investigation of the characteristics of double-purpose LIMs with opposite direction traveling magnetic fields.

## III. CONCLUSION

Thus, the preliminary studies of induction heating devices in a traveling magnetic field allow us to draw a number of conclusions:

- the possibility of low-temperature induction heating of the steel strip using three-phase linear inductors, whose windings can be cooled by air, is shown;
- it is confirmed that induction heating devices in a traveling magnetic field have higher energy indices than pulsating field devices;
- the effects of temperature equalization along the length of the heated strip are revealed with the use of a

traveling magnetic field and the application of traveling and pulsating fields, as well as the equalization of temperatures over the width of the strip in the case of a two-sided linear inductor with excitation of a longitudinal magnetic flux;

- demonstrated the possibility of creating double-purpose LIM, combining the functions of moving and heating metal products and blanks;
- the possibilities of using linear inductors with inadvertently traveling magnetic fields in induction heating devices in a traveling magnetic field are shown.

On the whole, the results of the studies confirmed the advantages of induction heating in a traveling magnetic field and the need for development of research works on the study of the characteristics of double-purpose LIM.

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